# Considering Turbofan Operability in Hybrid Electric Aircraft Propulsion System Design

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# Introduction

*Electrified aircraft propulsion (EAP) engine design:*

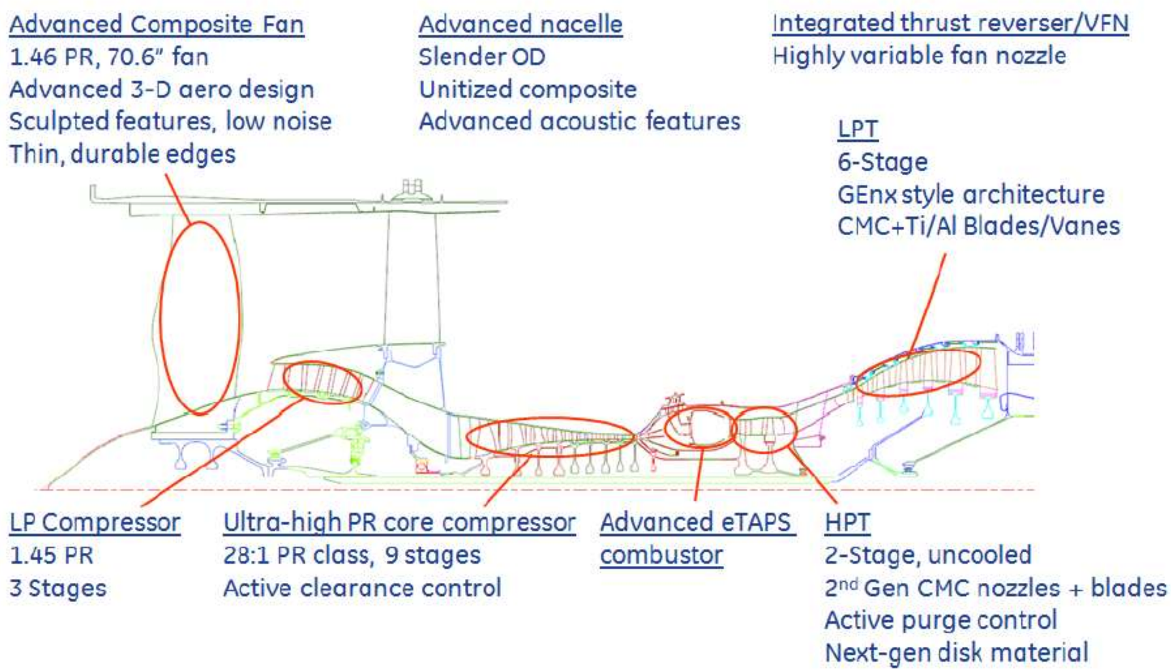
*Concepts using a turbofan to produce a large proportion of:*

- Thrust
- Power

- Generally, an engine is designed to produce thrust or power. When the engine is expected to produce large amounts of both a design dichotomy is created resulting in.
  - Operability issues (overspeed, surge margin)
  - Sizing issues (fan vs. electric machines)
  - Power generation vs. Thrust.

# Engine

*Engine baseline make use of the NASA gFan+ concept:*



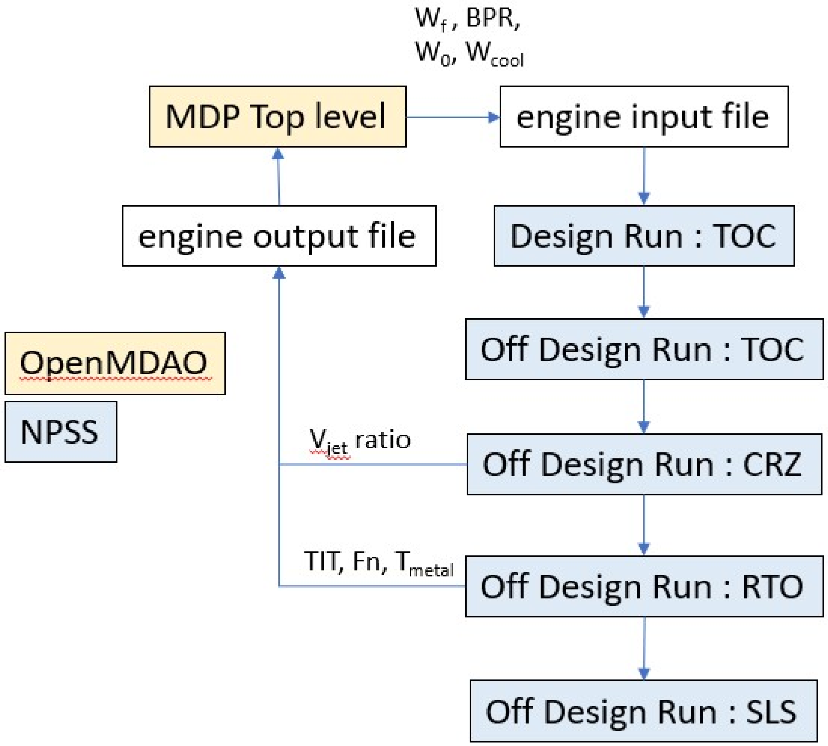

Highly advanced dual spool Turbofan engine

- High Bypass : 12 BPR
- TIT : 3440 degR
- Thrust : 22000 lbf
- TSFC : 0.486 lbm/hr/lbf

# Engine MDP design

*Multipoint engine design*

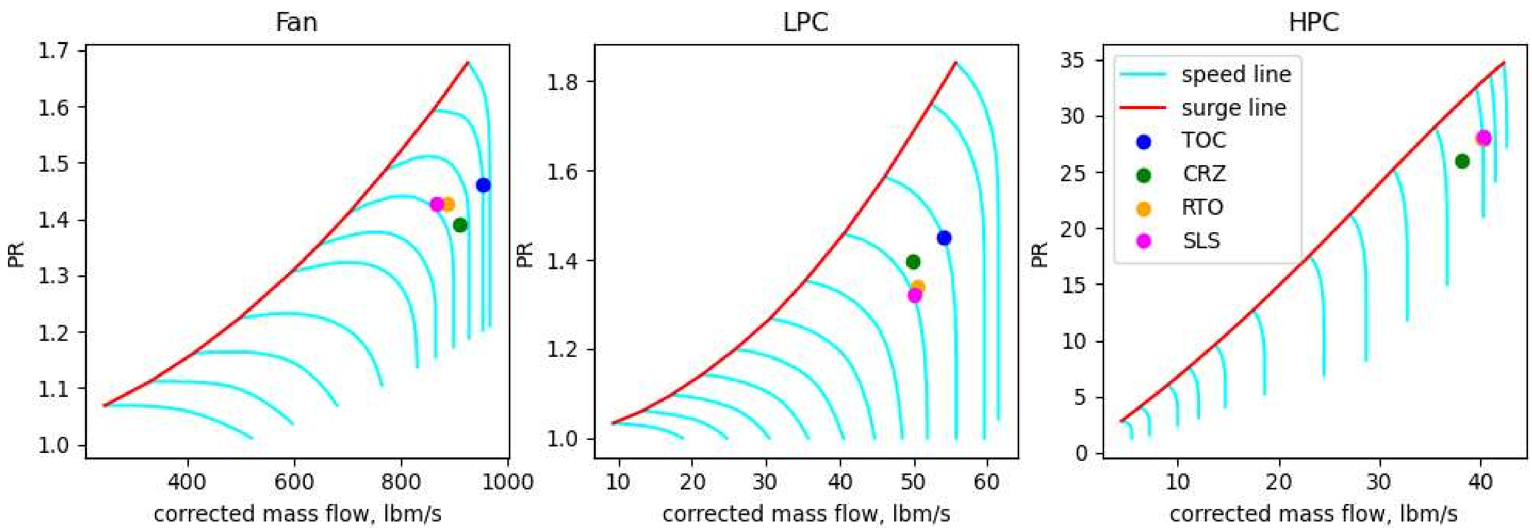
- ➢ Makes use of Numeric Propulsion Simulation System (NPSS) wrapped within OpenMDAO.
- ➢ Top of climb (TOC) is the engine sizing point sets speeds.
- ➢ Cruise (CRZ) is used to set bypass ratio
- ➢ Rolling take off (RTO) sizes air, fuel, and cooling flows.
- ➢ Sea level static (SLS) is run for comparison purposes



# MDP Baseline Design

*Map locations for MDP design*

- *Baseline engine with 0 power extraction and insertion*
- *Starting point for design space explortation*



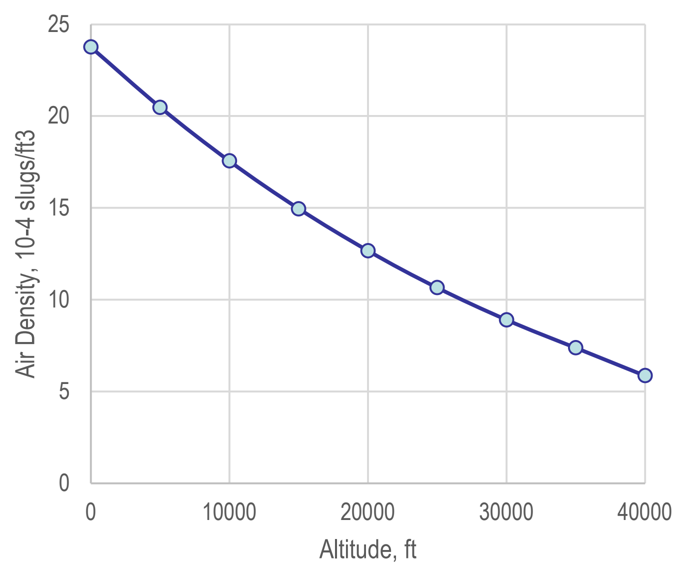
# Engine Lapse Rate

*Total engine power changes with operational point and is function of air density*

- Altitude
- Mach number

*Total engine power output is combination of:*

- Thrust
- Power extraction or insertion (electrical power)




Thrust and power extraction/insertion are not independent and must be coordinated as the engine is throttled or operating point changed

# Study overview

*Two main studies are completed :*

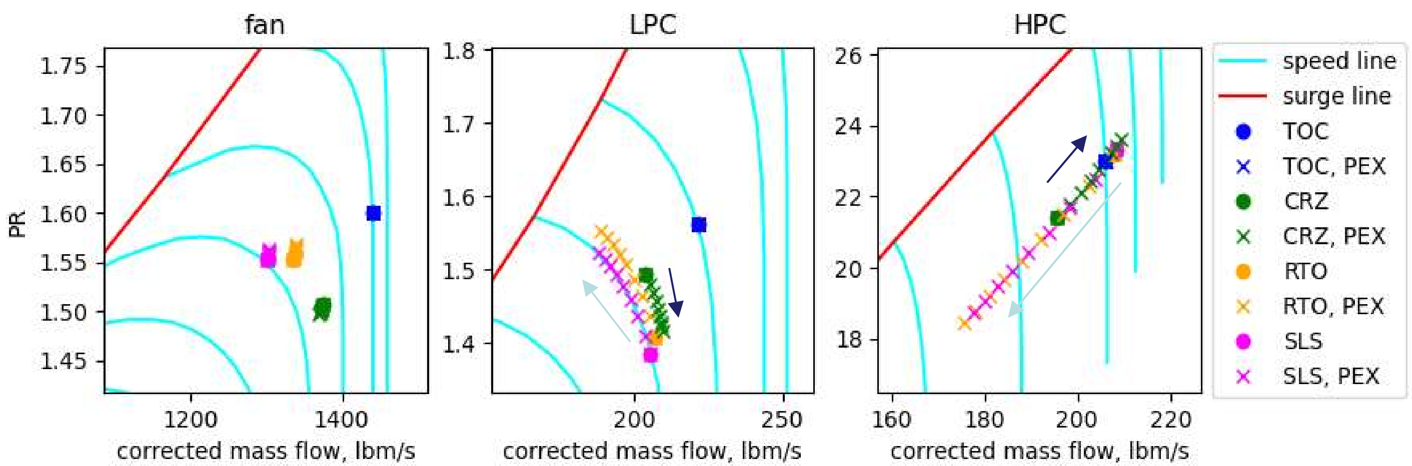
- Cruise thrust assist : power extraction (PEX)
  - Assumed distributed propulsion system will use power from engine to operate electrically driven propulsors
  - Power is extracted at cruise from low pressure spool
  - Power extraction beyond cruise point level is undesirable due to increased size of electric machines

- Take-off thrust assist : power injection (PIN)
  - Electrical power is used to boost engine during high power output reducing the size of the engine and allowing it to run at a higher more efficient power level at cruise
  - Power is injected at rolling take off from low pressure spool
  - Cruise operates with no power insertion

# Cruise Assist

*Engine designed with increasing LPS power extraction applied to all operating points:*

- *At RTO and SLS, LPC surge margin and HPC speed decrease*
- *At CRZ, LPC surge margin and HPC speed increase*
- *Limits observed must be observed in surge margin and HPC speed.*



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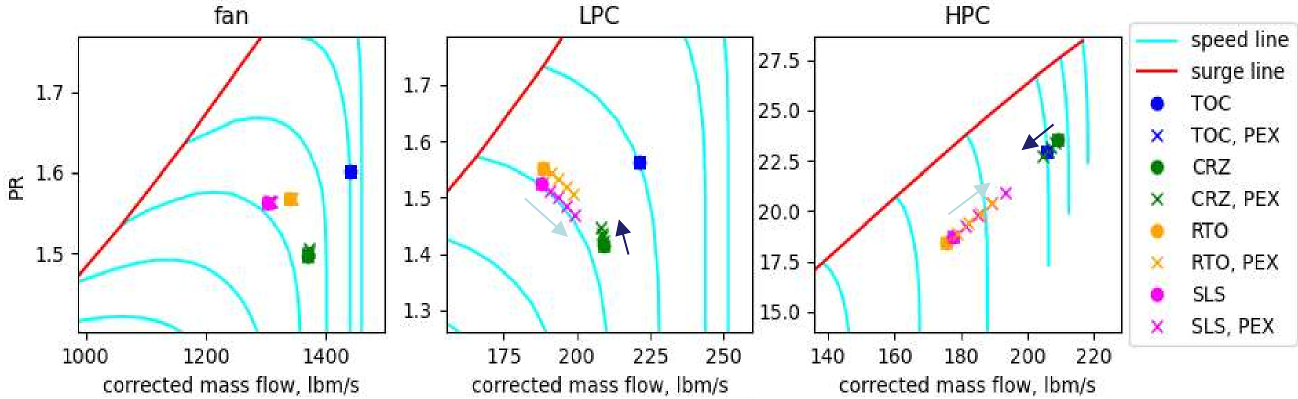
# CA Mitigating operability issues, additional power

*Balance operation by adding additional power extraction when engine total power output is higher than at cruise*

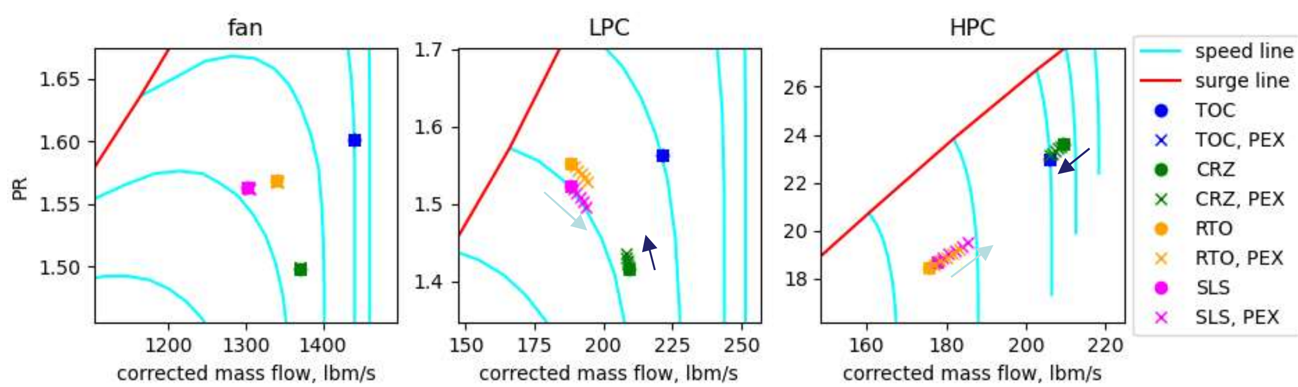
- *Increasing RTO and SLS power extraction*
- *At RTO and SLS, LPC surge margin and HPC speed increase*
- *At CRZ, increase in LPC surge margin and HPC speed*
- *Requires increasing the size of the electric machines*



# CA Mitigating operability issues, power split

*Balance operation by unloading high-pressure compressor*

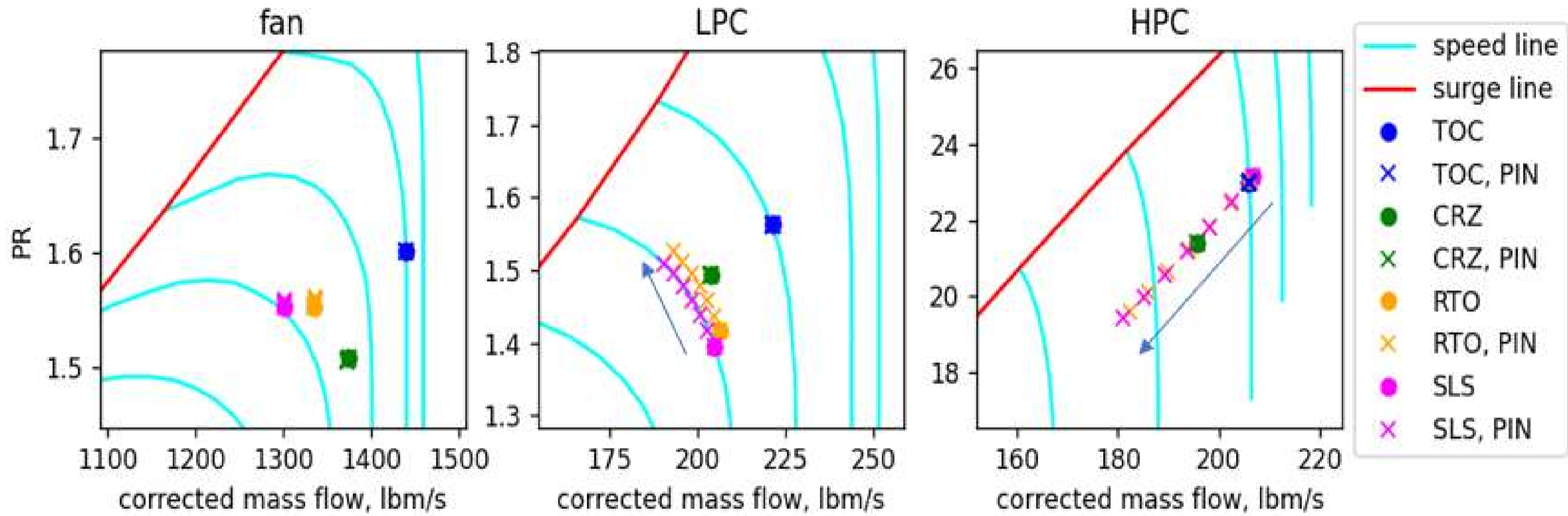
- *Adding HPS power extraction at TOC and CRZ, then removing this power extraction at SLS and RTO*
- *At RTO and SLS, LPC surge margin and HPC speed increase*
- *At CRZ, increase in LPC surge margin and HPC speed*
- *Requires adding electric machines to the HP shaft*



# Take off assist

*Engine designed with increasing LPS power insertion applied at RTO and SLS points:*

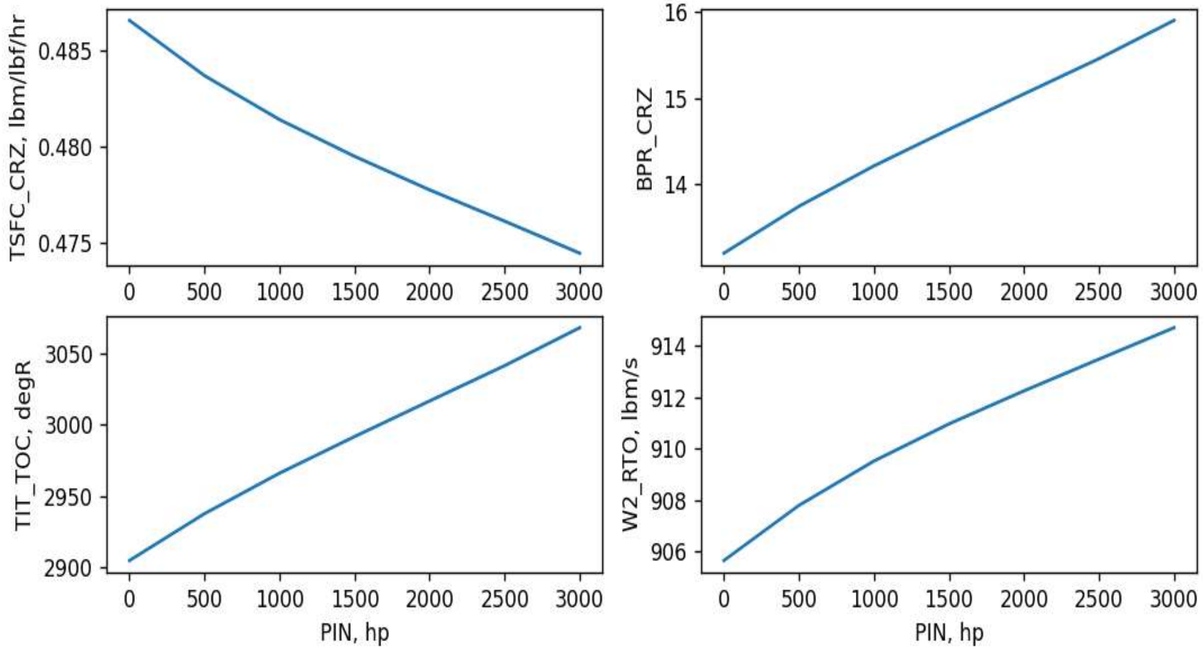
- *At RTO and SLS, LPC surge margin and HPC speed decrease*
- *Limits observed must be observed in surge margin and HPC speed.*



# Engine performance with Take off assist

*Key performance parameters with varying amounts of thrust assist (LPS power insertion at RTO and SLS)*

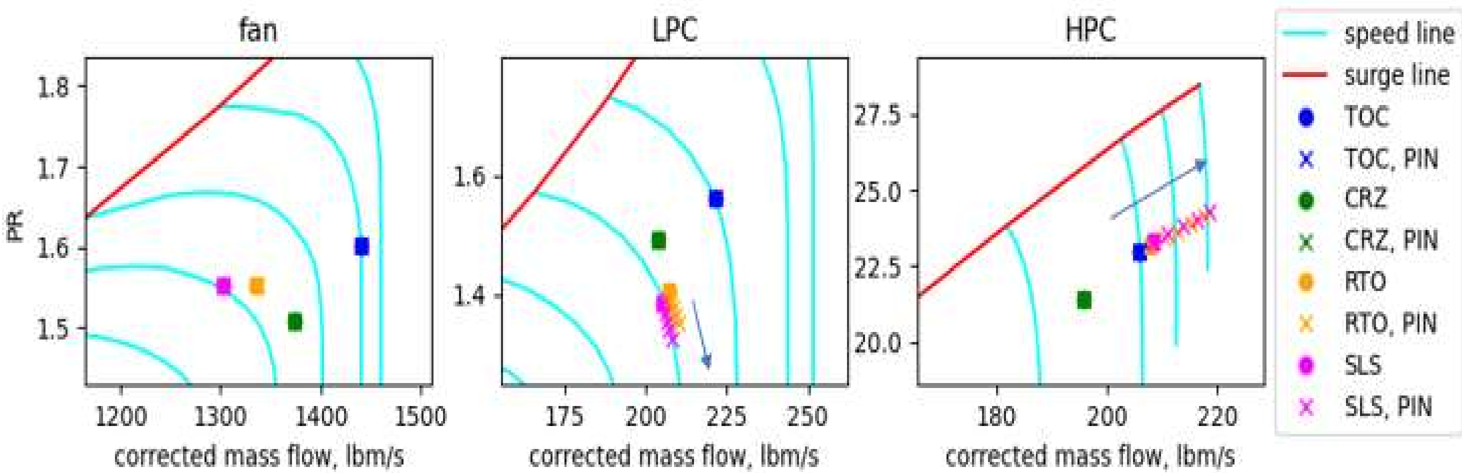
- *Take off assist shrinks core and increases bypass ratio*
- *Cruise thrust specific fuel consumption reduces*
- *Cruise and top of climb points operate at higher turbine inlet temperatures*



# TA Mitigating operability issues, HPS power insertion

*Replacing LPS power insertion with HPS power insertion:*

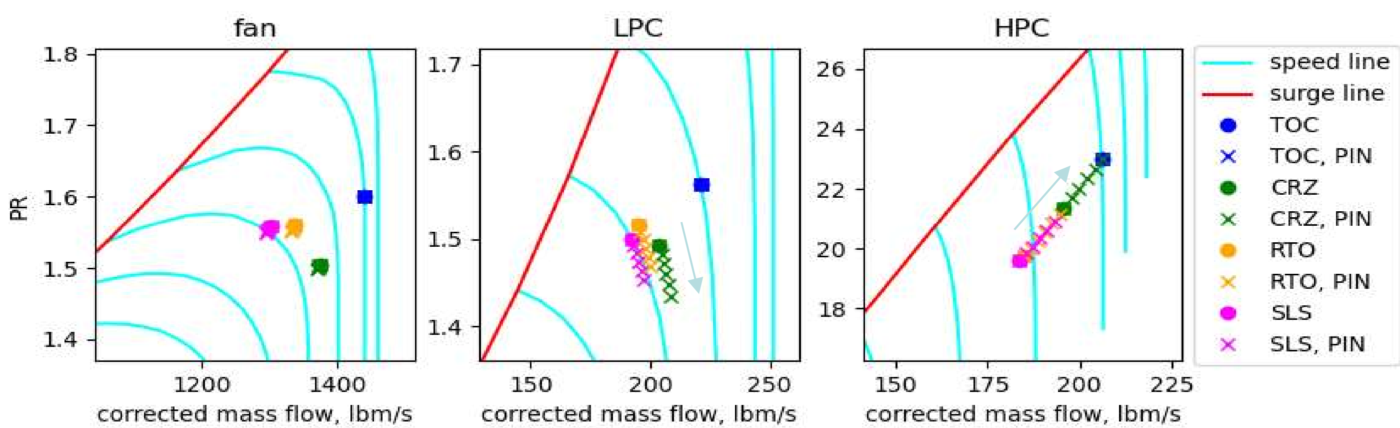
- *At RTO and SLS, LPC surge margin and HPC speed increase*
- *Thrust specific fuel consumption benefits much less than those developed with LPS power insertion*



# TA Mitigating operability issues, TOC power insertion

*Increasing power insertion at TOC to build margin in RTO and SLS limits:*

- *At RTO and SLS, LPC surge margin and HPC speed increase*
- *At CRZ, LPC surge margin and HPC speed decreases*
- *Thrust specific fuel consumption benefits much less than those developed with LPS power insertion.*



# TA combining method

*Making use of LPS power insertion, HPS power insertion and TOC power insertion allows the most power to be inserted onto the engine:*

- *Making use of LPS power insertion is the most efficient method of inserting power to gain cruise efficiency*
- *Using LPS and HPS power insertion allows for much more power ( nearly 2x) to be added to the engine, but the efficiency is less*
- *TOC offset increases the power moderately, but is much less efficient*

| | Baseline | LPS PIN at RTO | with HPS offset | with LPS TOC offset |
|---|---|---|---|---|
| LPS PIN, hp | 0 | 3470 | 5100 | 4512 |
| HPS PIN, hp | 0 | 0 | 1200 | 0 |
| Total PIN at RTO, hp | 0 | 3470 | 6300 | 4512 |
| TSFC at CRZ, lbm/hr/lbf | 0.486 | 0.471 | 0.4608 | 0.4696 |
| TSFC reduction from baseline, % | None | 3.09% | 5.19% | 3.37% |
| CRZ TSFC reduction per total PIN at RTO, %/(hp/1000) | None | 0.89% | 0.82% | 0.75% |

# Summary and Conclusions

*Designs of a turboshaft engine were completed with varying levels of power augmentation*

- Two main studies
  - Cruise Assist (distributed propulsion system) : Power extraction at cruise to enable high efficiency distributed propulsion concepts
  - Take off Assist : Power insertion at high power points to increase engine efficiency
- System designs demonstrate issues with LPC surge margin and HPC overspeed
- Operability issue mitigation
  - for cruise assist : increase RTO and SLS power extraction or update HPS/LPS power split
  - For take off assist : update HPS/LPS power split or increase TOC power insertion
- Take off assist shown to decrease cruise TSFC by over 5%

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